

*On the Absorption of Homogeneous  $\beta$ -Rays by Matter, and on the Variation of the Absorption of the Rays with Velocity.*

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The present work was undertaken with a view to establishing, if possible, the connection between the absorption and velocity of the  $\beta$ -rays. So far, no actual experiments have been performed on this subject, but Schmidt\* has determined the velocity of the rays emitted by radium E and uranium X. These have absorption constants of 40 cm.<sup>-1</sup> and 14 cm.<sup>-1</sup>, and their velocities, assuming the Lorentz formula for the variation of  $e/m$  with velocity of an electron, are 2.31 and  $2.76 \times 10^{10}$  cm. per sec. respectively. The matter has been attacked theoretically by Sir J. J. Thomson.† He deduces a formula connecting the “diffusion” coefficient of absorption with the velocity, and finds that the variation takes place inversely as the fourth power of the velocity.

Seitz‡ has made a series of experiments on the number of cathode particles passing through thin sheets of matter, and finds the coefficient of absorption to vary inversely as  $av^6 - bv^4$ , where  $a$  and  $b$  are constants and  $v$  the velocity of the electrons.

It has been generally assumed that a beam of homogeneous rays is absorbed according to an exponential law, and the fact that this law holds for the rays from uranium X, actinium, and radium E has been taken as a criterion of their homogeneity.§

This assumption is open to many objections, for the exponential law may be due to rays of different types being mixed in certain proportions. If the distribution of the rays and their velocity do not change in passing through matter, and if the absorption of the particles is proportional to the number present, we should expect an exponential law of absorption, but if their speed diminishes, the absorption should be greater the greater the thickness of matter traversed.

In the present experiments radium, which has been shown by Kaufmann||

\* Schmidt, ‘Phys. Zeit.’ 1907, p. 361.

† Sir J. J. Thomson, ‘Conduction of Electricity through Gases,’ 2nd edition, p. 376.

‡ Seitz, ‘Annalen der Physik,’ vol. 12, p. 860, 1903.

§ Hahn and Meitner, ‘Phys. Zeit.’ 1908, p. 321.

|| Kaufmann, ‘Gött. Nachr.’ 1903, p. 90.

to emit  $\beta$ -rays with velocities ranging between very wide limits, was used as a source of radiation, and by means of a magnetic field  $\beta$ -particles of different velocity were separated out and their absorption measured. Without entering at present into further details, it can be stated that the ionisation did not vary exponentially with the thickness of matter traversed, but, except for a small portion at the end of the curve, followed approximately a linear law.

The following experiments deal with this question and with the variation of the absorption of the  $\beta$ -rays with velocity.

*Experimental Arrangement.*

The general arrangement of the apparatus finally used is shown in figs. 1 and 2.

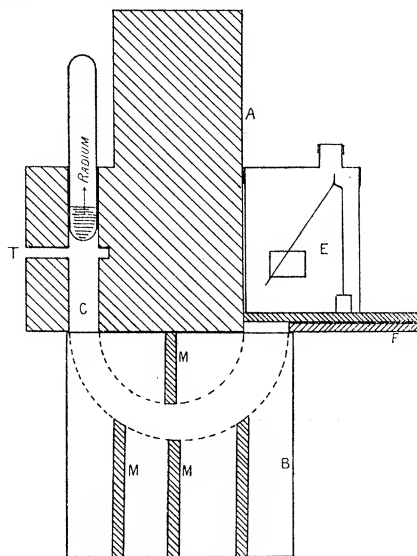


FIG. 1.

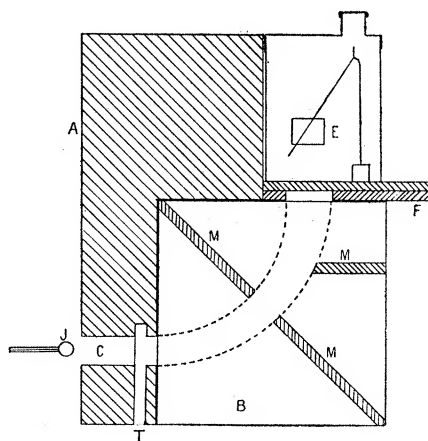


FIG. 2.

A lead block A, containing a hole C, 0.8 cm. in diameter, rested on the pole-pieces B of an electromagnet. In C was placed a glass tube containing about 30 milligrammes radium bromide. The preparation of radium employed was of about 7 per cent. purity, and it was found that most of the  $\beta$ -particles were absorbed before getting out of the active matter itself, so in the later experiments a corresponding quantity of radium emanation in equilibrium with its products, contained in a thin-walled bulb blown on the end of a capillary tube, was used as a source of radiation.

The chief experimental difficulty was the presence of a large  $\gamma$ -ray effect which, when the radium was used, often amounted to as much as

60 per cent. of the whole ionisation in the electroscope. To get the ionisation due to the  $\beta$ -rays alone this had to be subtracted from each reading of the ionisation, and the results consequently suffered in accuracy, especially when a few layers of absorbing material had been added, and the whole effect had become only slightly greater than that due to the  $\gamma$ -rays alone.

By the use of the emanation this effect was much reduced, and the accuracy of the results thereby greatly increased. With the arrangement shown in fig. 2 the  $\gamma$ -ray effect was not more than 20 per cent. of the whole, even for rays of very high or very low velocity.

The apparatus was arranged so that the rays could pass in a fairly well-defined beam into the magnetic field, which was perpendicular to the plane of the diagram. The field was found to be practically uniform, and the rays described circular paths and entered the small electroscope E through a hole 1.2 cm. diameter in a lead plate F. The distance from this hole to the hole from which the  $\beta$ -rays emerge is 3.9 cm., and from these data the curvature of the path of the rays could be determined. The radii of curvature for the arrangements shown in figs. 1 and 2 were 2.1 and 4.0 cm. respectively.

The electroscope was raised a little from the lead plate F, so that sheets of metal could be inserted in the path of the rays directly under the electroscope, and the variation of the ionisation with increasing thickness of matter determined. The field was measured by means of a Grassot fluxmeter, and also by comparing the induction through a small coil, whose necessary dimensions were known, when placed in the field, with a known induction. The two results were identical.

By pushing lead plates into the field at different distances from the base of the electroscope it was found that the rays were not scattered much in passing through the air, and that their paths were circles determined from the geometrical shape of the apparatus.

In order to reduce as much as possible the amount of scattered  $\beta$ -radiation which enters the electroscope, and also to ensure a greater purity of the rays used, lead screens were placed as shown at MMM. These, it will be seen, will from their positions very effectively cut out rays reflected from the pole-pieces, etc.

In addition to these reflected rays there is a large amount of secondary radiation set up by the  $\gamma$ -rays. The effects due to this cause were eliminated as follows: After every reading of the ionisation in the electroscope a lead plate of sufficient thickness to absorb all the  $\beta$ -rays which fell on it was pushed into the slot T and prevented any  $\beta$ -rays from entering the

magnetic field. At the same time it was so thin that the  $\gamma$ -ray effect on the pole-pieces, etc., was practically unaltered. In the second type of apparatus care had to be taken to place the slot in such a position that the lead plate did not come in the direct path between the radium and the electroscope. The value of the ionisation now found in the electroscope gives the amount to be deducted for both direct and secondary  $\gamma$ -radiation. A certain amount of secondary  $\beta$ -radiation is set up in the screen itself by the  $\gamma$ -rays, but since only that portion of this reaches the electroscope which has exactly the same properties as the rays we are considering, it will not affect the results.

The procedure in making an experiment was as follows: The field was adjusted to the right strength, and the ionisation in the electroscope measured. A reading was then taken with the lead plate in position, and the ionisation thus found subtracted from the previous reading. This was repeated for every layer of absorbing material which was placed under the electroscope.

#### *Form of Absorption Curves.*

As stated before, the ionisation in the electroscope was found not to fall off, according to an exponential law, with the thickness of matter traversed, but more rapidly the greater the distance penetrated. For the rays of higher velocity the relation was linear, except when the radiation had been cut down to a large extent, when it fell off more slowly with increasing thicknesses of matter.

Curves showing the absorption of the rays for some different velocities are shown in fig. 3 and in fig. 4. In the latter, the logarithm of the ionisation is plotted against the thickness of matter traversed. This brings out the difference between the law of absorption found and the exponential law more strongly. For the very easily absorbed rays the linear law was not so strongly marked, and the reason for this will be discussed later.

#### *Reliability of the Experiments.*

Experiments were then performed to determine whether the effect observed is really a property of the rays or due to the experimental conditions.

Three causes which might possibly influence the absorption curves are:—

1. Lack of saturation of the ionisation current.
2. The shape and size of the electroscope and of the opening by which the rays enter.
3. The proximity of the magnetic field to the electroscope, which might cause irregularities by bending the rays inside it.

The first of these was tested for by comparing the time taken for the gold leaf to go over two widely different portions of the scale for various values of ionisation. If the ratio remains constant it is a proof of saturation.

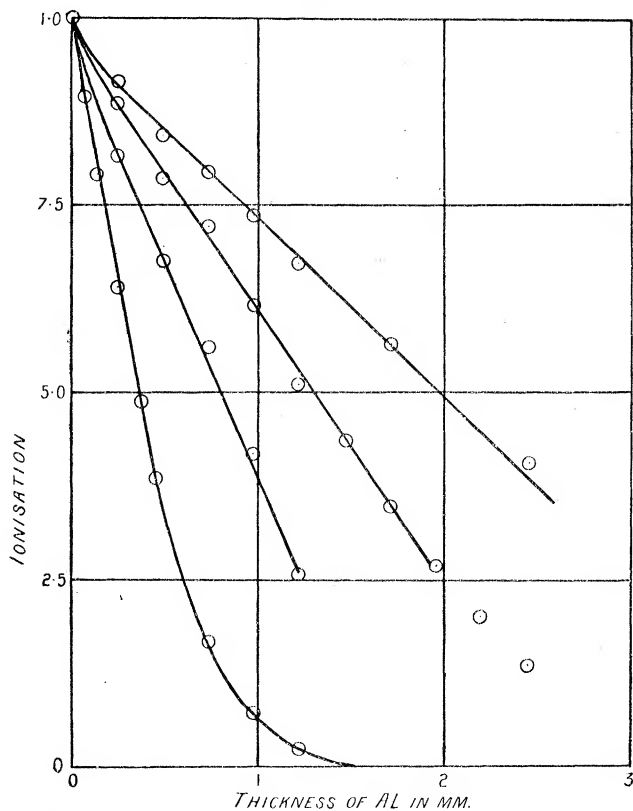


FIG. 3.

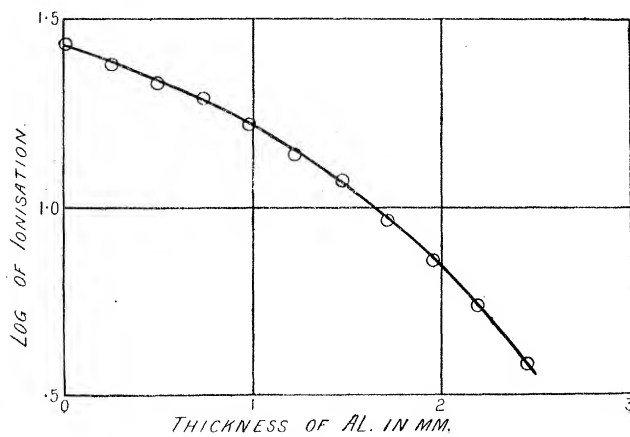


FIG. 4.

Saturation was found to be complete. A further test which fully confirms the other was made by measuring the absorption curves for the same type of rays, the strength of the sources being in the ratio of about one to eight. The two curves were identical.

The second point was tested for by placing a tray containing a preparation of actinium under the electroscope and determining the absorption of the  $\beta$ -rays emitted by it. It was found to be an exponential law with the coefficient of absorption  $30 \text{ cm.}^{-1}$ , which is the value obtained when measured in the ordinary way.

A magnetic field was then applied to test the third point, and the same law of absorption still held good. A small amount of radium emanation in equilibrium with its products was also placed under the electroscope and no difference in the absorption curves for the  $\beta$ -rays emitted by it resulted when a magnetic field was applied.

Further, the absorption curves obtained, using the two types of apparatus shown in figs. 1 and 2, are practically the same, although the magnetic field required to deflect the same type of rays into the electroscope is much greater in the first place than in the second.

It also seemed possible that the effect might be due to the rays striking the absorbing screen at right angles and becoming more and more scattered as they penetrate the matter. This would cause their path to become more tortuous and the rate of absorption would be thereby increased. That this is not the case was seen by allowing a practically parallel beam of actinium rays to fall normally on a screen placed under a larger electroscope, when the absorption still took place according to the general exponential law found for these rays.

#### *Variation of Absorption with Velocity.*

We have seen that the absorption of homogeneous  $\beta$ -rays, when measured by the ionisation, takes place according to a linear law. The relation between ionisation and thickness of matter traversed is given by  $I = k(a-x)$ , where  $a$  is the thickness of matter for which the ionisation would become zero if the law were rigorously true, and  $ka$  the initial ionisation.  $a$  determines the rate of absorption of the rays and is a constant for rays of a given velocity. Absorption curves were determined for rays of different velocities, using aluminium, copper, and tin as absorbing substances. The values obtained for the variation of  $a$  for aluminium with velocity are given in Table I. The velocity was calculated from the value of magnetic field  $\times$  radius of curvature of the rays by means of the formula  $HR = mv/e$ , where  $H$  is the strength of the field and  $R$  the radius of curvature of the rays.

$e/m$  is determined by means of the Lorentz formula,  $\frac{e}{m} = \frac{e}{m_0} \left(1 - \frac{v^2}{c^2}\right)^{\frac{3}{2}}$ , where  $c$  is the velocity of light and  $e/m$  the ratio of the charge to the mass of the electron for low velocities. The value of  $e/m_0$  is  $1.74 \times 10^7$  electromagnetic units.

If we define the absorption coefficient as  $\lambda$ , where  $dI = -\lambda I dx$ ,  $I$  being the ionisation and  $x$  the thickness of matter traversed, we obtain from our previous equation

$$k = \lambda k(a - x).$$

The initial value of  $\lambda$  is therefore  $a^{-1}$ . With this law of absorption  $\lambda$  is not constant, but increases as the thickness of matter traversed by the rays is increased. The values of the initial value of  $\lambda$  are given in the fourth column of Table I. The values of  $a$  are plotted against HR and velocity in figs. 5 and 6 respectively, and in fig. 7 the initial values of  $\lambda$  are plotted against HR.

On account of the very complicated nature of the effects influencing the determinations of the absorption coefficients, it is not probable that any simple expression can be obtained connecting the values of  $a$  or  $\lambda$  with the velocity. Between velocities  $2.1$  and  $2.9 \times 10^{10}$  cm. per sec. the following relation gives a very good agreement—

$$a = 5.5 \left( \frac{mv}{e} - 1500 \right) 10^{-4}$$

for aluminium as absorbing substance, where  $a$  is expressed in millimetres.

For copper the equation is

$$a = 1.2 \left( \frac{mv}{e} - 1000 \right) 10^{-4}.$$

Table I.

R.	HR.	V.	$a$ .	$\lambda$ .
cm.	Gauss cm.	$10^{10}$ cm.	mm.	cm. <sup>-1</sup> .
4.0	1310	1.79	0.14	71.5
	1860	2.20	0.26	38.5
	2760	2.545	0.70	14.3
	3860	2.74	1.32	7.6
	4450	2.795	1.67	6.0
	5390	2.855	2.08	4.81
	6350	2.899	2.64	3.79
	8000	2.920	3.29	3.04
	8580	2.930	4.09	2.44
	8960	2.937	4.69	2.13
	980	1.46	0.095	105.0
	1820	2.19	0.235	42.5
2.1	2160	2.35	0.35	28.6
	2640	2.515	0.535	18.7
	3300	2.665	0.96	10.4
	4300	2.782	1.28	8.35
	5190	2.844	2.00	5.00
	5490	2.859	2.12	4.17

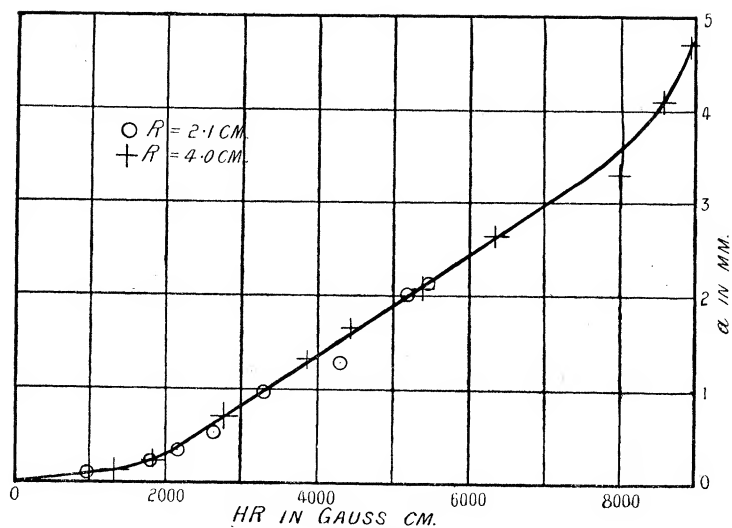


FIG. 5.

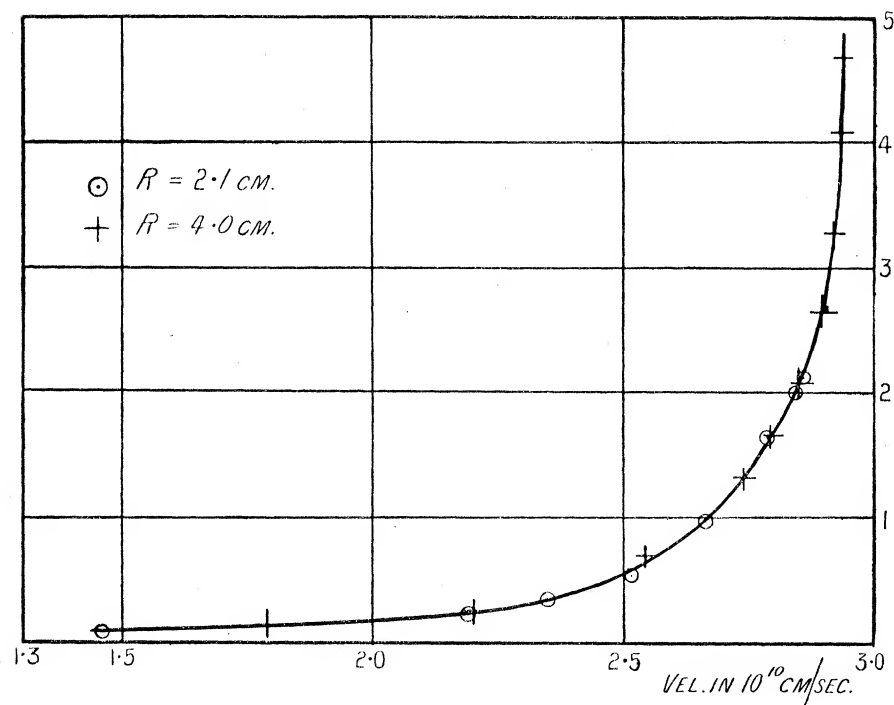


FIG. 6.

In Table II the values of  $\alpha$  for different velocities of rays when copper and tin were used as the absorbing media are given. The linear law of absorption

does not appear to hold so well for these substances as for aluminium, but the departure from the exponential law is still very great. For copper, fairly definite values of  $a$  could be obtained, but with tin the values are only

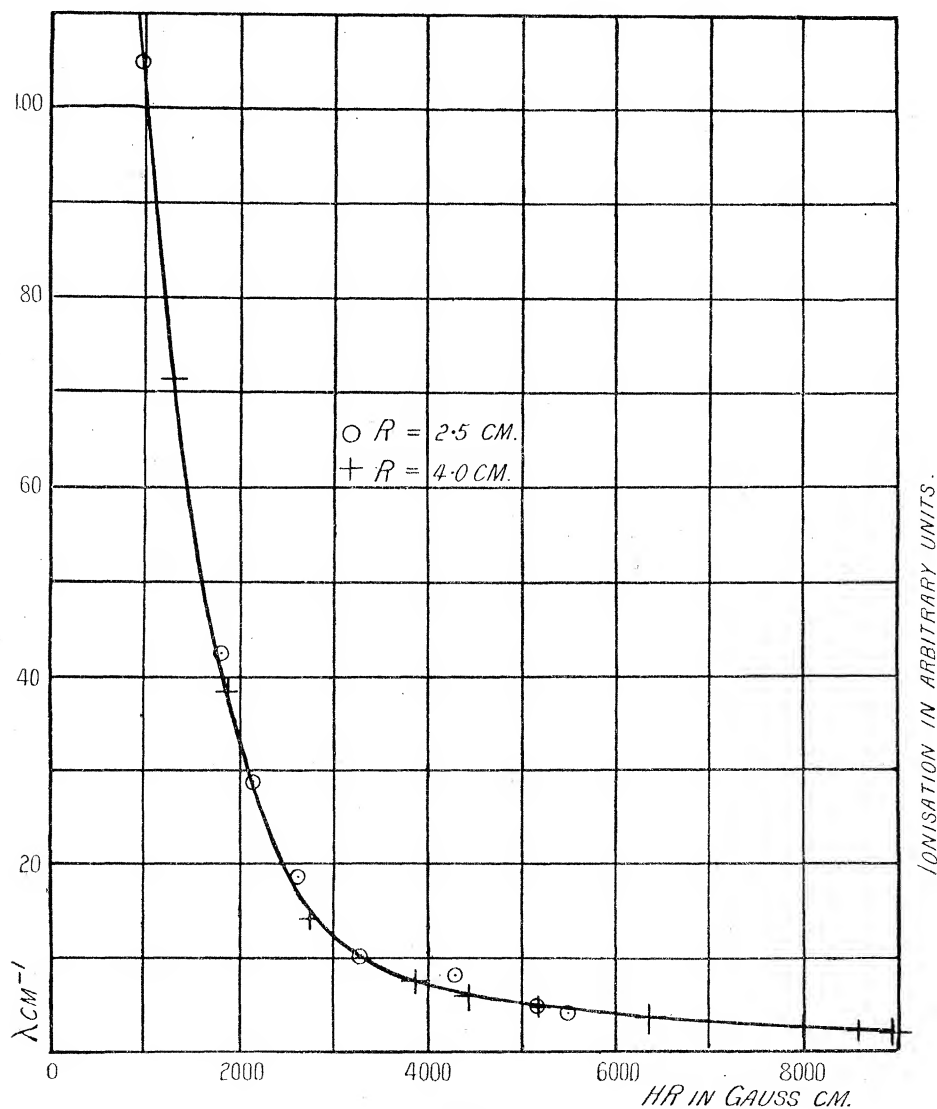


FIG. 7.

approximate. The indeterminate character of the curves obtained for tin is very likely connected with the secondary radiation from it, as peculiarities in this connection have been noted by all other observers who have worked on this type of experiment.

It will be interesting to consider the effect of the density of the absorbing substance on the absorption curves, but more experiments will have to be performed before anything definite can be said on this point.

Table II.

HR.	$a$ in mm.	
	Tin.	Copper.
1860	0.130	0.118
3130	0.370	0.275
4400	0.626	0.430
6350	0.775	0.700
8570	0.940	0.985

The values of  $a$  given for copper in Table II are plotted in fig. 8 against the values of HR.

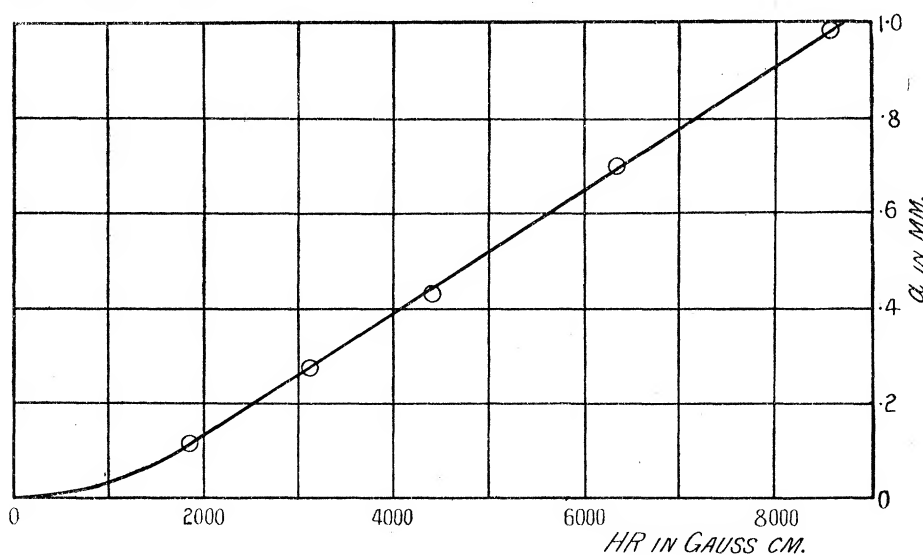


FIG. 8.

*Explanation of the Exponential Law found by various Observers for the Absorption of Rays from Radio-active Substances.*

Before entering into a discussion as to the meaning of the absorption curves obtained, it is preferable to try to explain why various observers have found that the rays from uranium X, radium E, and actinium are absorbed according to an exponential law with the thickness of matter traversed.

The fact that homogeneous rays are not absorbed according to an exponential law suggests that the rays from these substances are heterogeneous. Now, Schmidt\* gives a curve *which to some extent* shows the manner in which the rays from uranium are distributed about their mean velocity. Using a similar arrangement to the author, he obtains a curve, shown in fig. 9 (*a*), in which the ionisation in the electroscope is given for different field strengths.

The area of this curve, then, represents the ionisation we would get in the electroscope if all the rays of all velocities from the uranium were allowed to enter together, instead of being deflected into the electroscope separately by the magnetic field.

From the absorption curves we have found we can determine the amount by which the rays corresponding to each separate portion of the curve are absorbed, and so can build up a similar curve for the rays after passing through any thickness of matter. Curve *b*, fig. 9, is a specimen curve obtained in this manner, showing the distribution of ionisation with magnetic

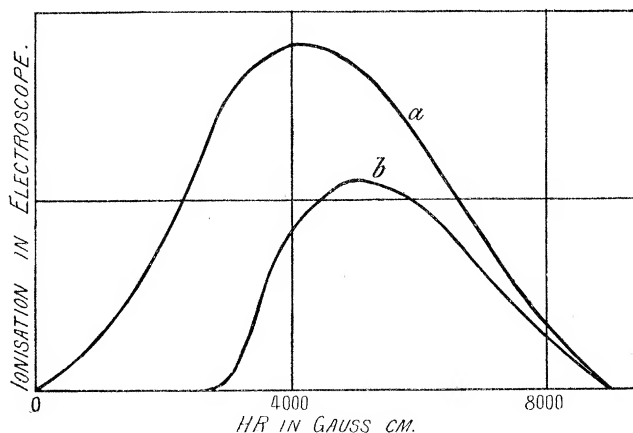


FIG. 9.

field after the rays have passed through 0.6 mm. of aluminium. The more slowly moving rays are completely absorbed, while the ionisation due to the more rapid particles has only decreased by a small amount. The areas of such curves give us the ionisation we would get in the electroscope if all the  $\beta$ -rays from the uranium were allowed to enter it together after passing through the corresponding thickness of aluminium.

In Table III are given the areas found in the above manner for curves drawn for many different thicknesses of aluminium.

\* Schmidt, 'Phys. Zeit.,' January 1, 1909.

Table III.

Thickness of aluminium in mm. traversed.	Area in arbitrary units.	Log of area to base 10.
0	746	2·873
1	658	2·818
2	556	2·745
4	437	2·640
6	341	2·533
8	262	2·418
10	204	2·310
12	158	2·199
14	121	2·082
16	90	1·954
20	55	1·740

The values given in this table are plotted in fig. 10, and it will be seen that the curve is an exact exponential whose absorption coefficient is

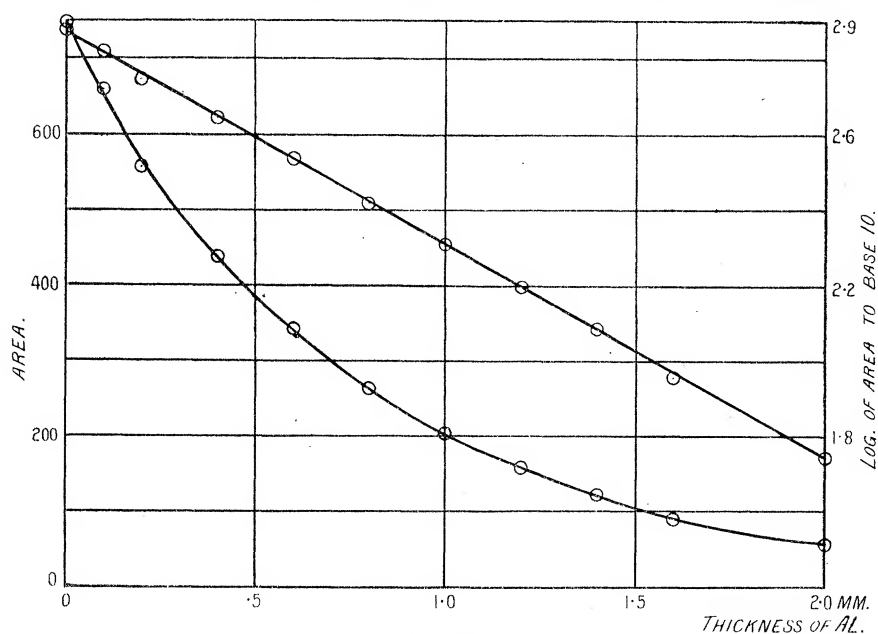


FIG. 10.

$13.1 \text{ cm.}^{-1}$ , a value not very different from that observed for the  $\beta$ -rays of uranium by Rutherford,  $13.7$ , and Schmidt,  $14$ . The curve extends over quite a wide range, the final area being about one-thirteenth of the initial one. It is thus clear that the exponential curve for absorption of rays is not, as has been widely assumed, a test of their homogeneity, but that in order that the exponential law of absorption should hold, we require a mixture

of rays of different types. This view of the subject is strongly confirmed by some recent experiments of Soddy,\* who finds that the rays from uranium are heterogeneous, some having velocities which correspond to  $HR = 6500$ . The mean velocity according to Schmidt† is that corresponding to  $HR = 4110$  Gauss cm.

We have seen that for any special velocity of rays the ionisation due to them after passing through a thickness of matter  $x$  is given by  $i = k(a - x)$ , where  $a$  determines the rate of absorption, and is fixed by the velocity of the rays, while  $ka$  is determined by the initial value of the ionisation.

If we now assume that the numbers of the particles in a heterogeneous beam are distributed with regard to  $a$  in such a manner that the ionisation due to the rays of each particular velocity is  $af(a)$ , the ionisation due to them after passing through a thickness of matter  $x$  is given by

$$i = f(a)(a - x).$$

The ionisation due to the whole number of particles entering the electro-scope together would be

$$I = \int_x^\infty f(a)(a - x) da.$$

Now if  $I$  decreases with  $x$  according to an exponential law, we have

$$I = I_0 e^{-\lambda x} = \int_x^\infty f(a)(a - x) da.$$

From this equation we obtain  $f(a) = \lambda a I_0 e^{-\lambda a}$ ; or  $af(a)$ , which gives the initial ionisation for each different velocity of rays, is  $\lambda a I_0 e^{-\lambda a}$ .

This is somewhat of the same type as the distribution of velocities used in problems on the kinetic theory of gases, but differs from it in the power to which  $e$  is raised. It has a maximum when  $a = \lambda^{-1}$ .

We thus see that it is possible to obtain a heterogeneous beam of particles, of which the different types of rays are absorbed according to a linear law, but the absorption of the whole beam takes place according to an exact exponential law.

#### *Mechanism of the Absorption of the $\beta$ -Rays.*

There are two ways in which the absorption of a beam of particles can take place. In one the particles lose energy as they pass through matter and finally cease to be effective as ionising agents. This has been shown to be the manner in which the absorption of the  $\alpha$ -rays takes place. In the other the particles are stopped in mid career while their velocity is still high, and

\* Soddy, 'Le Radium,' February, 1909.

† *Loc. cit.*

Schmidt\* and McClelland and Hackett† have with considerable success worked out a theory in which particles are assumed to pass through matter with a constant velocity, a sudden stopping of a certain proportion of the rays taking place in each thin layer of the matter. This view has received considerable support from some experiments of Makower,‡ who, by measuring the actual number of the  $\beta$ -particles from radium getting through various thicknesses of matter, has shown that this number varies in exactly the same manner as the ionisation.

Sir J. J. Thomson has considered the question from a theoretical standpoint and finds that if the absorption is due to scattering and stopping alone, the law it follows should be exponential with the thickness of matter traversed.

Crowther§ finds that scattering is "complete" after the rays have passed through very small thicknesses of matter, and Hahn and L. Meitner have shown that when a parallel beam of the  $\beta$ -rays from actinium strikes the absorbing screen perpendicularly there is only a slight deviation from the exponential law of absorption.

These experiments are against the view that the increase of the absorption coefficient for greater thicknesses of matter which we have found is due to the rays striking the absorbing screen normally and becoming more and more scattered as they pass through the matter.

#### *Change of the Velocity of the Rays in passing through Matter.*

Schmidt|| has also attacked this problem, using as a source of radiation the rays from radium E. He deflected the rays in a similar manner to that described above into an electroscope by means of a magnetic field and obtained a curve connecting ionisation in the electroscope and strength of field. From the strength of field for which the ionisation was a maximum he deduced the velocity of the rays, and found that the position of the maximum point did not alter if he allowed the rays to pass through different thicknesses of aluminium before entering the magnetic field. From this he concluded that the velocity of the rays does not change appreciably in passing through matter. The absorption curves obtained in my experiments, however, suggest that the velocity of the rays decreases with thickness of

\* Schmidt, 'Jahr. der Rad.,' 1908; and 'Ann. der Physik,' 1907, vol. 23, p. 671.

† McClelland and Hackett, 'Roy. Soc. Dubl. Trans.,' vol. 9, No. 4, 1907.

‡ Makower, 'Phil. Mag.,' January, 1909.

§ Crowther, 'Roy. Soc. Proc.,' A, p. 308, 1908.

|| Schmidt, 'Phys. Zeit.,' June, 1907.

matter traversed and further experiments on this point were made as follows:—

In fig. 11, curve *a*, is shown the connection between ionisation and the electroscopes strength of field when a certain preparation of radium is used as a source of radiation. As in the case of the uranium rays (fig. 9), we

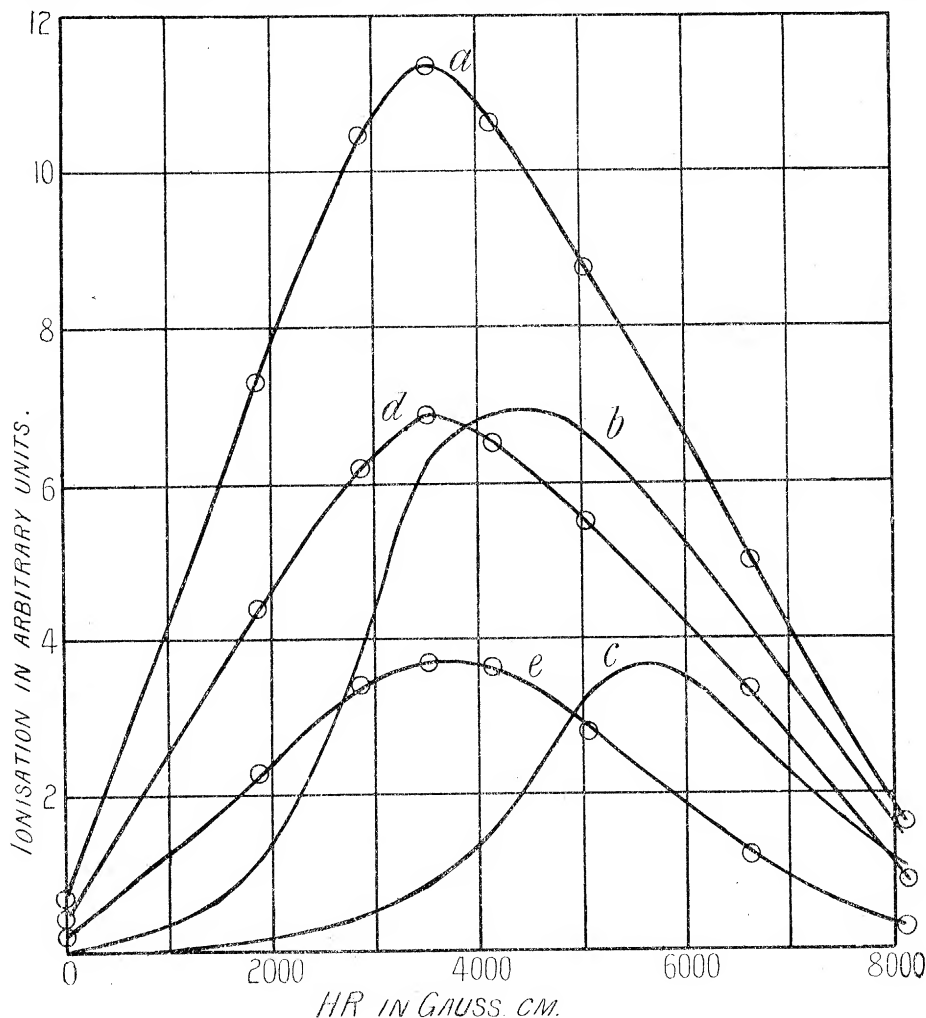


FIG. 11.

can determine the shape of this curve after the rays have passed through various thicknesses of matter. Curves shown at *b* and *c* for the rays after passing through 0.489 and 1.219 mm. of aluminium were obtained experimentally by varying the field while sheets of aluminium of a given thickness were placed *under the electroscope*. The rays from the radium were

then allowed to pass through screens of these thicknesses placed at J (fig. 2) *before entering the magnetic field.*

If the particles do not decrease in velocity in passing through the matter, the curves obtained in this case connecting ionisation with strength of magnetic field should fall on *b* and *c*. If the velocity decreases, however, they should fall to the left of these. This was found to be the case, the curves being shown in the figure at *d* and *e*, and the particles therefore decrease in velocity as they pass through the matter.

The velocity is found from the position of the maxima to fall from  $2.78 \times 10^{10}$  cm. per sec. to  $2.69 \times 10^{10}$  cm. per sec. while the rays passed through 0.489 mm. of aluminium, and from  $2.865 \times 10^{10}$  cm. per sec. to  $2.69 \times 10^{10}$  cm. per sec. while they pass through 1.219 mm.

This experiment also explains why the experiments of Schmidt apparently show no change in the velocity of the rays. According to the views expressed in this paper he was dealing with heterogeneous rays and the position of the maximum should therefore move to the higher fields if the velocity of the rays does not change. The actual decrease in velocity, however, brings the maximum point back to practically the same position as before.

*Deviation from the Linear Law.*

The bending away of the final portions of the absorption curves from the straight line may be due to three causes :—

1. The size of the hole from which the  $\beta$ -rays emerge, and by which they enter the electroscope, makes the beam of rays used in these experiments not quite homogeneous. This would cause the more rapidly moving rays to become relatively more and more important as the rays traverse the matter, and a departure from the straight line should therefore be observed. Experiments made without the screens MMM (figs. 1 and 2) give curves which depart earlier from the straight line. The rays in this case are more heterogeneous, and this is what we should expect.

2. The  $\gamma$ -ray effect, which has to be subtracted from each reading of the ionisation, also increases relatively in importance as the rays penetrate matter, and its exact value is very hard to determine. If its effect were taken slightly too small it would produce a deviation from the linear law, in the direction observed.

3. As Sir J. J. Thomson points out in "Conduction of Electricity through Gases," p. 378, the mechanism of the absorption is not the same for the slow rays which cannot penetrate the atom and rapid ones which can do so. The departure from the law may be due to this cause, and also to changes in the ionisation produced by the rays on account of their decrease in velocity.

4. It is very probable that if we start with quite homogeneous rays, after they have passed through matter they will become heterogeneous owing to the velocity of each separate particle not being altered by the same amount.

The fact that the absorption curves for low velocities do not show the linear law so strongly marked as those of high velocities is very likely in part due to the greater heterogeneity of the rays; but there is also a great likelihood that this law would not even hold for pure slow rays. The law depends on a variety of conditions which require for their full consideration data not yet acquired, and it is more than likely that the conditions change very much with the velocity of the rays, and the linear law propounded can only be regarded as approximate.

#### *Conclusions.*

The results obtained in this paper can be summed up as follows:—

1. The absorption by matter of homogeneous  $\beta$ -rays does not take place according to an exponential law, when measured by the ionisation, but according to a law which is practically linear.

2. The rays emitted by such substances as uranium X, radium E, and actinium are heterogeneous, and groups of rays can be built up which represent their properties with respect to absorption.

3. The  $\beta$ -rays decrease in velocity in passing through matter.

4. The variation of the absorption of the  $\beta$ -rays with velocity has been determined experimentally, but does not appear to follow any simple law.

I wish to thank Prof. Rutherford for suggesting the subject of this research, and for his great help and encouragement during its progress.

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### *The Properties of Colloidal Systems. I.—The Osmotic Pressure of Congo-red and of some other Dyes.*

By W. M. BAYLISS, F.R.S.

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